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An Automated 20–20,000-cps Transmission Measuring Set for Laboratory Use

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An automated loss and phase measuring set has been developed to measure, in a point-by-point fashion, two-port networks over the frequency range from 20 to 20,000 cps with a maximum accuracy of 0.01 db and 0.1 degree. Manual, semiautomatic, and automatic modes of operation are provided. During automatic operation, the interval between successive data points is determined by programmed intervals of frequency, loss, and phase. These quantities are programmed either separately or in combination. Machine selection of the measurement points is controlled by comparing the program with information fed back from the signal oscillator and the measured circuit. At each selected point, frequency is measured, loss and phase are determined by self-balancing standards, and these data are recorded on punched tape.

I. INTRODUCTION

Automatic measurement techniques have been widely and successfully applied in situations where many repetitive measurements of a similar type are required. In many cases the measuring instruments are programmed for a specific measurement or sequence of measurements, and versatility is of minor importance. This paper describes an automatic transmission measuring set that was developed for laboratory use in the 20- to 20,000-cps frequency range to measure two-port networks having a wide variety of characteristics.

The first section of the paper specifies the quantities that are measured and the range and accuracy of the measurements, and lists the functions that the skilled operator of a manual measuring set must perform when making laboratory measurements. In Section II some of the factors involved in data taking are discussed, and the chosen method of automatic data selection is described. Section III describes, in broad terms, the measuring and control circuits used. Operation of the automated set in the manual, semiautomatic, and automatic modes is described in Section IV. A more detailed description of the measuring and control circuits, along with a description of some of the more important subsystems, is given in Section V. In Section VI some of the most important systems considerations which influenced the measuring set design are discussed. Section VII gives the results of tests made to confirm the measuring set accuracy and to evaluate, using selected networks, the operation of the automatic control and data selection functions of the measuring set.

1.1 *Required Measurements, Accuracy and Ranges*

The basic quantities measured are the insertion loss and phase shift of a two-port network as a function of frequency when measured between 600-ohm unbalanced impedances.[1] The measurement frequency is continuously variable from 20 to 20,000 cps and adjustable to ± 0.1 cps. The input power level to the measured network is variable in 5-db steps from $+10$ dbm to -20 dbm, each step being accurate to ± 0.25 db. The range of loss measurement is from 0 to 120 db with an accuracy of ± 0.01 db for losses less than 40 db. Phase shift is measured from 0 to 360° with an accuracy of $\pm 0.1°$ for losses less than 40 db. Measurements can be made at impedances other than 600 ohms by changing a pair of plug-in terminations, but the oscillator output level will not be calibrated, and the loss and phase measurements may not be direct reading.

1.2 *Function of the Measuring Set*

Measurements are required for adjustment of networks and for obtaining data which can be processed by a computer or recorded in tabular or graphical form. In obtaining data with a manually operated set, the operator must choose and select the measurement frequencies, make the loss and phase measurement, and record the data. Any fully automatic set must also carry out these functions and, in particular, must provide a way of introducing the necessary inputs into the set so that the required data will be obtained.

II. SELECTION OF DATA POINTS

The a priori knowledge of the behavior of the networks being measured will not always be sufficient to enable the network designer to preselect the frequencies at which the measurements should be made in order that no important details be missed. If the frequency interval between successive measurements is made small, all the important details will be detected, but this would increase the over-all time required to make the measurements and give superfluous data. Unneeded data may not be objectionable when recorded in graphical form, but stored digital data should be kept to a minimum. In order to select only meaningful data on a network with uncertain characteristics, some form of feedback is needed when selecting the data points. When making manual measurements, a skilled operator supplies this feedback.

To illustrate several criteria by which a machine can select data points, an arbitrary loss characteristic is illustrated in Fig. 1(a). If a certain frequency interval, Δf, were to be chosen as the interval between measured points, important parts of the characteristic would be missed if a smooth curve were drawn through the points taken as shown in Fig. 1(b). Application of this criterion does not require any feedback from the measured network.

If the same characteristic were to be measured by using a selected increment of loss, ΔL, to determine the measured points, the characteristic would be completely determined within $\pm\Delta L$. This is shown in Fig. 1(c). The loss interval criterion does require feedback. It can be seen that the effect of the frequency "comb" (Δf criterion) is that fine structure may be missed, but coarse structure is reproduced pretty well. The effect of the loss "comb" is to reproduce fine structure well, but large area errors may occur when coarse structure is measured.

Application of the frequency and loss "combs" together results in a much better reproduction in general than either can do alone. Fig. 1(d) shows a smooth curve drawn through the measured points taken by the use of both criteria simultaneously. The same remarks hold for phase measurements in which a selected increment of phase, $\Delta\theta$, is used to select measured points.

In the general measurement case, the criteria used to select data points in one part of the frequency range may not be the desirable criteria for another part of the frequency range. The bandpass filter shown in Fig. 2 may be used to illustrate this. Typically, one would be interested only in the coarse loss structure in the stop bands and what the minimum loss is to within perhaps 3 db. Another item of interest might be the loss slope in the transition regions or fine variations of the loss and phase in the

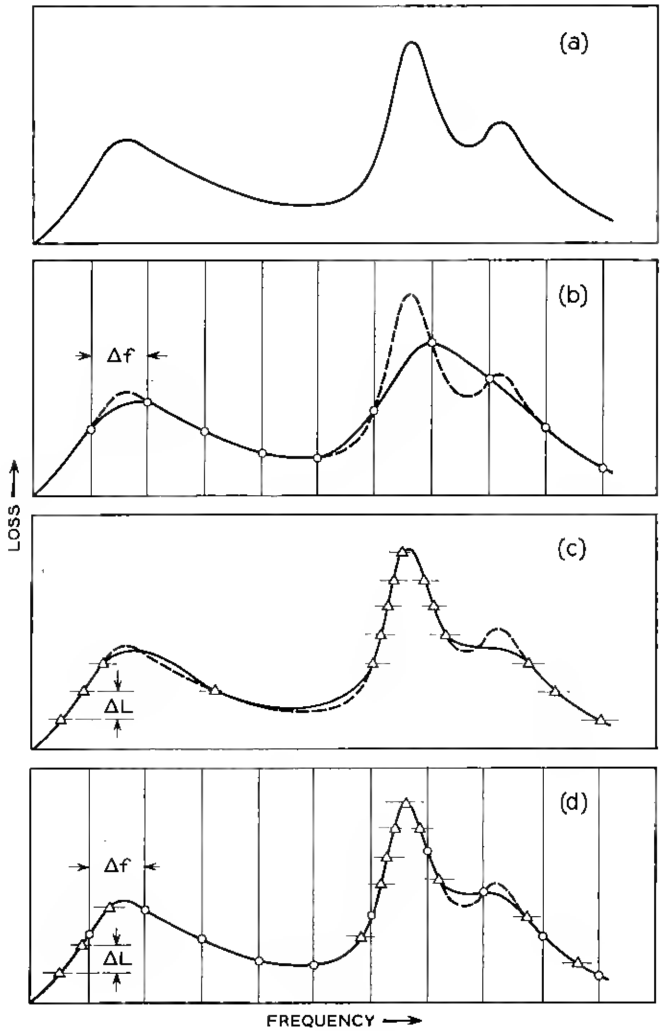

Fig. 1 — Criteria for data selection.

passband, because these characteristics influence carrier transmission. Thus, the choice of which criteria to use and the size of the chosen intervals will vary in different frequency bands.

In the data selection method adopted, a program control is provided which permits Δf, ΔL, and $\Delta\theta$ intervals to be set up independently in each of 5 frequency bands. The Δf intervals are 1000, 300 and 100 cps; the

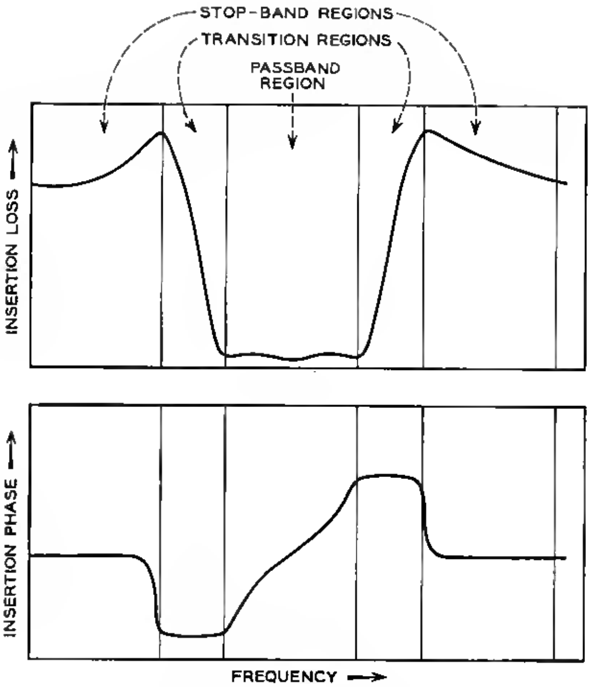

Fig. 2 — Bandpass filter transmission characteristic.

ΔL intervals are 10, 3, 1, 0.3, 0.1 and 0.03 db; and the $\Delta\theta$ intervals are 30, 10, 3, 1 and 0.3 degrees. The edges of the bands can be set to any arbitrary frequency in the 20- to 20,000-cps range to the nearest 10 cps.

III. BLOCK DIAGRAM OF THE TRANSMISSION MEASURING SET

The block diagram of the measuring set can be conveniently divided into two parts, the measuring circuit and the control circuit.

3.1 *Measuring Circuit*

A simplified block diagram of the measuring circuit is shown in Fig. 3. The signal oscillator, adjusted to the measurement frequency F, is applied to the unknown and to the loss standard. As the sampling switch S_1 rapidly compares the outputs from the two paths, any difference in transmission between the unknown and the loss standard will result in variations of the measurement frequency level and phase at the switching rate.

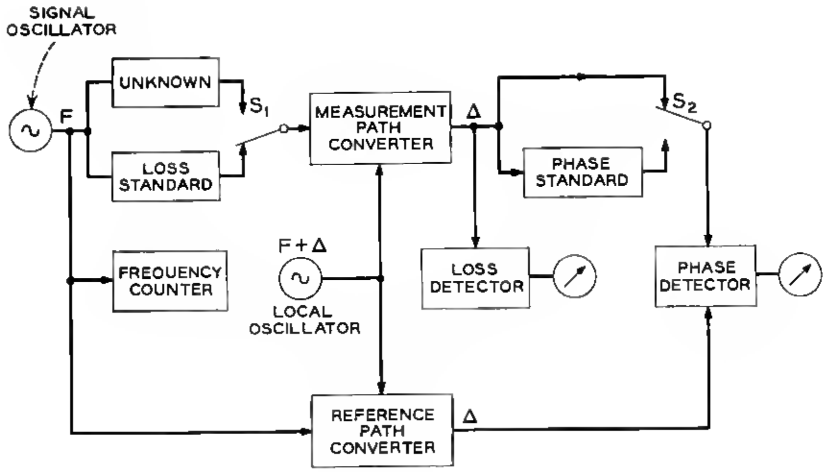

Fig. 3 — Simplified block diagram — measuring circuit.

These level and phase variations at frequency F are linearly translated to level and phase variations at the fixed frequency Δ by the measurement path converter. The level differences at the converter output are detected by the loss detector and indicated by proportional deflections on the loss detector meter. When the loss standard is adjusted to have loss equal to that of the unknown, the loss detector meter will indicate a null. The loss measurement is then completed by recording the setting of the loss standard.

For the phase measurement, a second path is needed to provide a reference signal for the phase detector. The output from the measurement path converter is applied to the phase standard and the strapped path, and switch S_2 is switched synchronously with S_1. The phase standard is adjusted until the phase at S_2 is the same for both switch positions, this condition being indicated by a null on the phase detector meter. If the phase of the loss standard is negligible, the phase of the unknown will then be equal to the phase of the phase standard. The frequency counter measures the signal oscillator frequency, and recording the setting of the phase standard and frequency counter completes the measurement of a point.

3.2 *Control Circuit*

In Fig. 4 the control circuit is added to the measurement circuit. Self-balancing controls for the loss and phase standards have been added along

with automatic readout. Automation of the set is accomplished by the addition of the over-all control and the oscillator sweep control. The over-all control consists of selector switches for setting up the measurement program; a range control circuit to sense the band in which the oscillator frequency, F, is located; loss and phase detectors to sense the magnitude of the loss and phase changes; and a frequency control circuit used in frequency interval programming. Before discussing the circuit operation in more detail, the three operating modes of the measuring set will be described.

IV. OPERATION OF THE MEASURING SET

The three modes of operation for the set are manual, semiautomatic, and automatic. Regardless of which mode is selected, the operator must connect the network to be measured, adjust the terminal impedances if

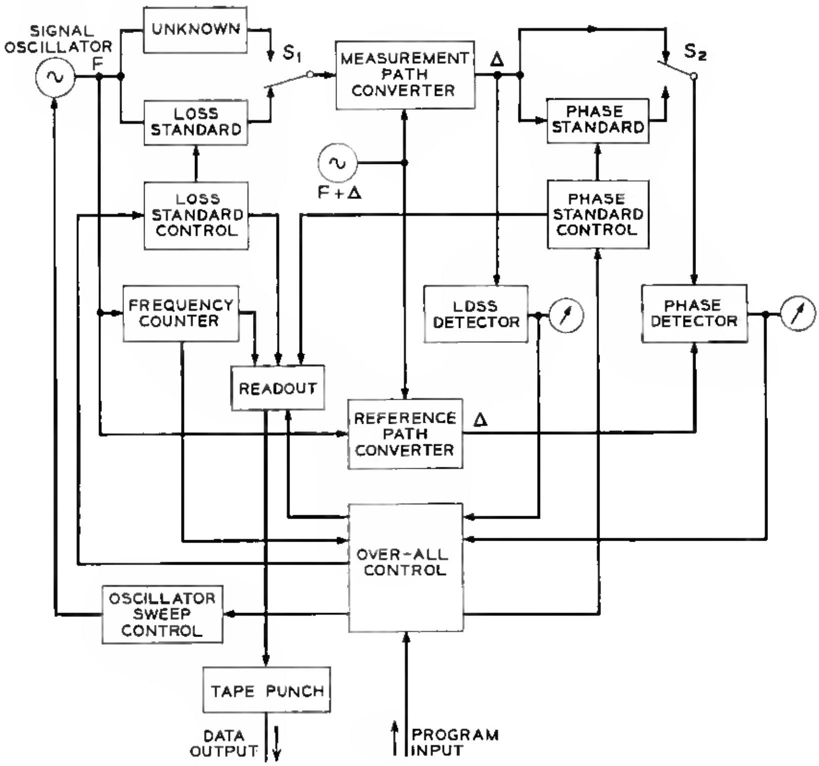

Fig. 4 — Simplified block diagram — measuring and control circuits.

they are to be different from 600 ohms, and select the oscillator output level. Fig. 5 shows the console arrangement of the set.

4.1 *Manual Operation*

In the manual operating mode, the oscillator can be manually adjusted to ± 5 cps by means of the coarse tuning control used in conjunction with a film scale. The fine tuning control, when used with the frequency counter, makes it possible to set frequency to ± 0.1 cps. The frequency counter is operated by a pair of pushbutton controls to give either a 1-second or 10-second time base.

Relay switching of the IF filters makes two detector bandwidths available in the manual mode, one bandwidth being 10 times the other. The narrower bandwidth is normally used when the measurement frequency is below 500 cps or at other frequencies when the maximum available signal-to-noise ratio at the detector is desired.

Manual adjustment of a set of decade switches is required to balance the loss standard. The loss unbalance indication is provided in analog

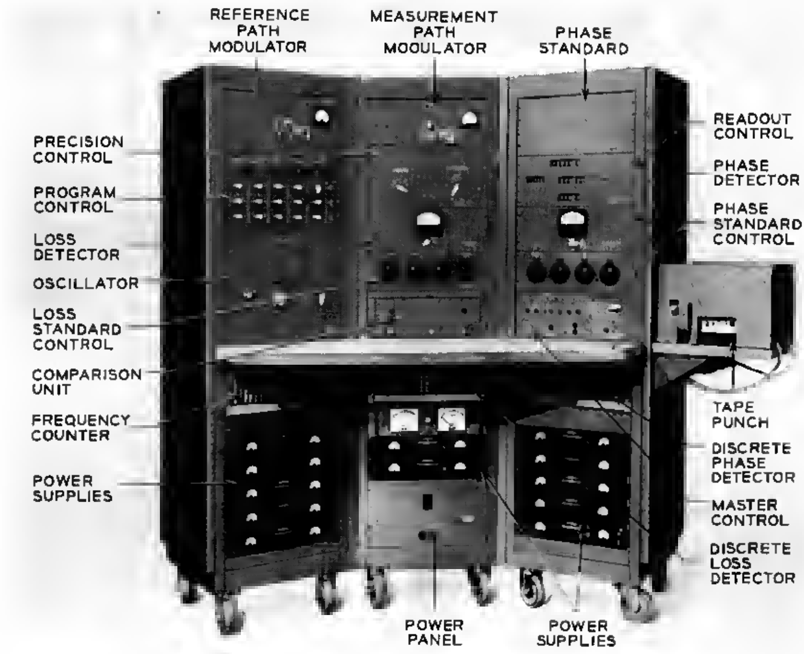

Fig. 5 — Console arrangement of transmission measuring set.

form by a calibrated meter with 3 scales and in digital form by indicating lamps placed just above the decade switches. These lamps indicate which decade switch should be adjusted to obtain a balance. The manual phase balance is obtained in the same way by means of similar indications.

After the frequency has been measured and the loss and phase standards balanced, the measured values appear on the visual readout panel. Data can either be recorded manually or punched on paper tape by operating the print out pushbutton.

The oscillator can be swept in the manual mode by operating the coarse tuning control. As the frequency is changed, indications of the loss and phase variations in the measured network can be obtained from the analog and digital indicators of loss and phase unbalances.

4.2 *Semiautomatic Operation*

Operation of the set in the semiautomatic mode permits the operator to initiate, by means of pushbutton controls, any step in the sequence which forms the automatic operating cycle. The controls for the separate steps are labeled "balance loss," "balance phase," "read frequency," "display data," "print out," and "sweep frequency." Front panel lamps are placed above each control to indicate operation of the set in each one of these steps. Operation of the balance loss control results in automatic switching of the loss standard pads in an ordered sequence to achieve balance. Automatic balance of the phase standard is initiated by operation of the balance phase control. The loss and phase balances are made to a precision which depends either on the absolute loss or on the setting of a manual precision control.

The read frequency control has the same function as in the manual mode: that is, to initiate a frequency measurement with either a 1-second or 10-second time base.

The function of the display data step is to store on the visual readout panel the readings of the loss standard, phase standard, and frequency counter.

As in the manual mode, operation of the print out control causes the data to be recorded on paper tape.

The choice of the frequency for the next data point may be made by the operator or by the program control. In the latter case, the range control, Δf, ΔL, and $\Delta\theta$ switches are set for the desired program, and operation of the sweep frequency control causes the oscillator to sweep until one of the programmed intervals is exceeded.

It remains only to note that the sequence just described is not rigid, and the various steps can, with a few exceptions, be interchanged in sequence or omitted. For example, if the phase shift of a network is not of interest, the balance phase step can be omitted.

4.3 *Automatic Operation*

In the automatic mode, the operator must manually set the oscillator to the minimum frequency of interest and set up the desired measurement program. The precision of frequency measurement must be set to 0.1 cps, 1 cps, or programmed. In the programmed position, the precision is 0.1 cps at measurement frequencies below 500 cps and 1 cps above 500 cps. After the start control is operated, the set will cycle continuously until all desired data is taken. Each cycle consists of 5 steps: balance loss, balance phase, read frequency, print out, and sweep frequency. Each cycle is timed, and in the event that a cycle is not completed in a prescribed time, an alarm signal occurs. This alarm also signals the end of a run.

V. DESCRIPTION OF SUBSYSTEMS IN THE MEASURING SET

Fig. 6 is a partially simplified block diagram of the measuring set, including the control circuits. Functioning of the over-all system will be more readily understood if some of the subsystems are considered separately, so the oscillator, loss measuring circuit, phase measuring circuit, programming circuit, and some of the other important circuits will be separately described.

5.1 *Oscillator*

A detailed block diagram of the oscillator is shown in Fig. 7. The oscillator is of the heterodyne type, containing one crystal oscillator fixed at 97 kc and one LC oscillator which is variable from 97.02 to 117 kc. The oscillator modulator converts these two frequencies to the measurement frequency, which can be varied from 0.02 to 20 kc in a single range. The stability of the oscillator output frequency is 0.1 cps over the period of a measurement. Two AGC loops are employed in the oscillator to obtain an output flat with frequency to ± 0.1 db. The level select pads which follow the power amplifier are used to adjust the level applied to the circuit being measured.

Tuning of the variable oscillator is controlled by three capacitors. Coarse tuning is accomplished with a servo-driven, variable air capacitor geared to a 200-inch film scale. The servo can be operated manually with

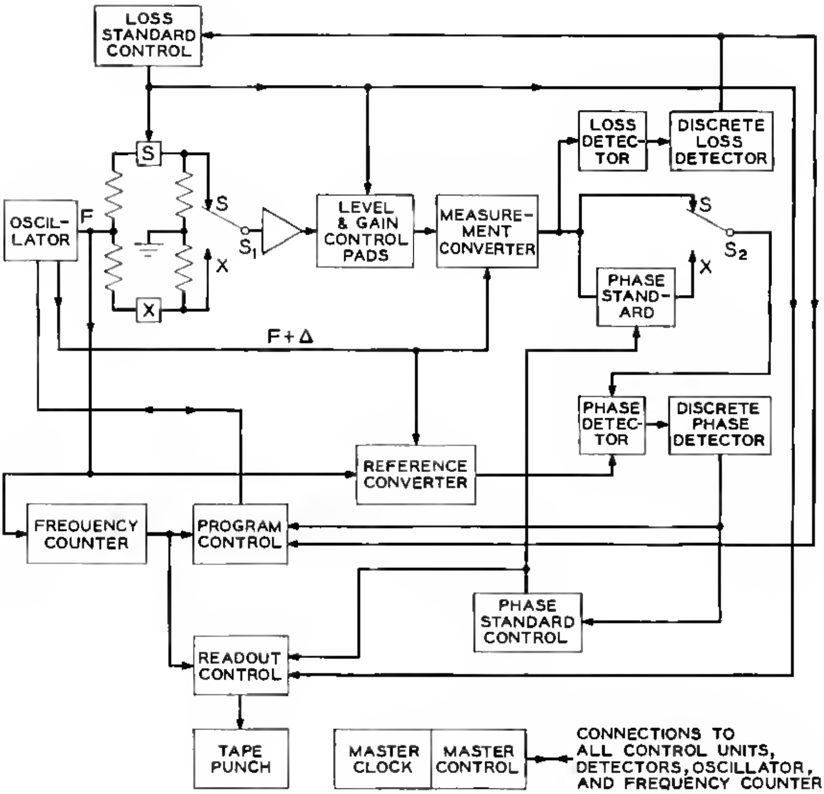

Fig. 6 — Simplified block diagram — measuring and control circuits.

the coarse tuning control or automatically with signals from the program control. A small variable air capacitor mounted on the front panel provides the manual fine tuning control, and the third capacitor is voltage controlled for operation in an AFC loop.

When the AFC relay is operated, the voltage-controlled capacitor is connected to the LC oscillator. The control voltage for the variable capacitor is obtained from a phase detector which has as its inputs the measurement signal and a precise 100-cps frequency. If the open-loop measurement frequency is witbin ±10 cps of a 100-cps multiple, energizing the AFC relay will cause the measurement frequency to lock to this 100-cps multiple with no frequency error.

A lamp and a photodiode are used with the film scale to detect 100-cps multiples as the measurement frequency is being swept. A decimal

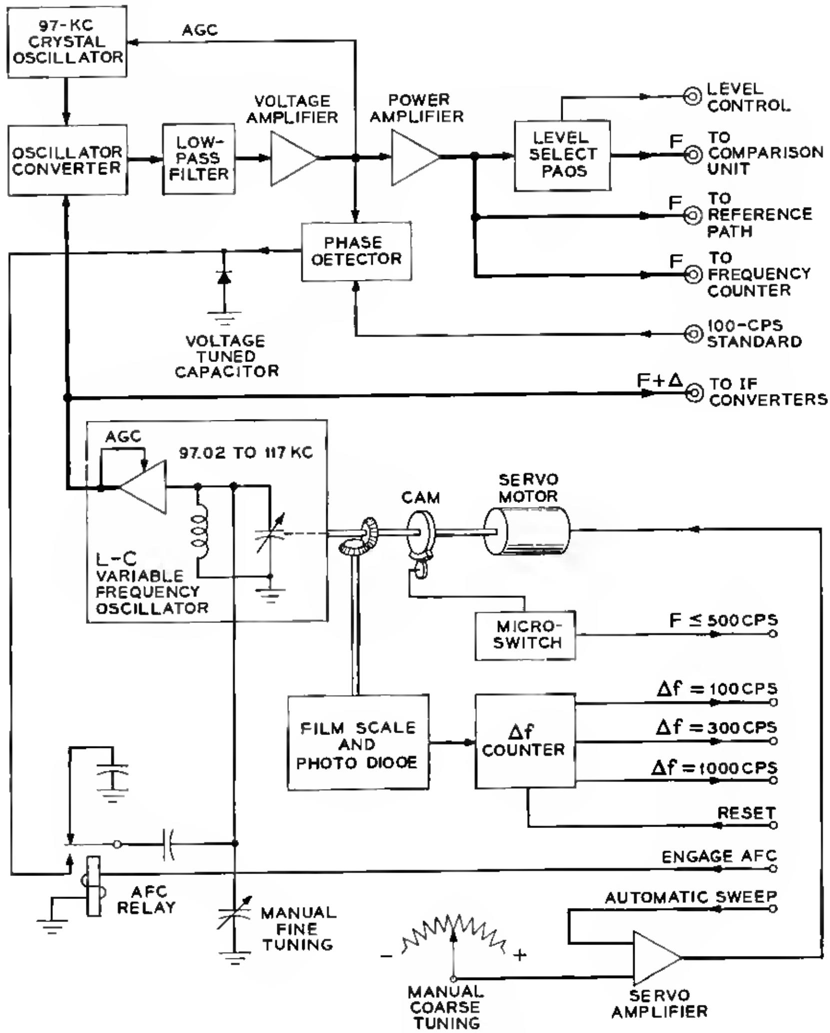

Fig. 7 — Oscillator block diagram.

counter is used to provide indications for frequency intervals of 100, 300, and 1000 cps.

A cam, mounted on the coarse tuning capacitor shaft, operates a microswitch to select the narrow-band IF filter during automatic operation at measurement frequencies below 500 cps.

5.2 *Loss Measuring Circuit*

Fig. 8 shows the loss measuring circuit together with the self-balancing circuit. The test signal from the oscillator, after being attenuated to the desired level by the output level selector, is applied to the loss standard and the unknown. The loss standard consists of relay-switched attenuator pads, which can be inserted in 0.01-db steps from 0 to 119.99 db.

The outputs from the standard (S path) and unknown (X path) paths are alternately sampled by a mercury relay operating at either 10 cps or 1.6 cps, depending on whether the wideband or narrow-band IF filter is used. The sampling relay is followed by a high-impedance buffer amplifier, so that the input levels and terminating impedances for the standard and unknown paths are essentially constant. This permits the

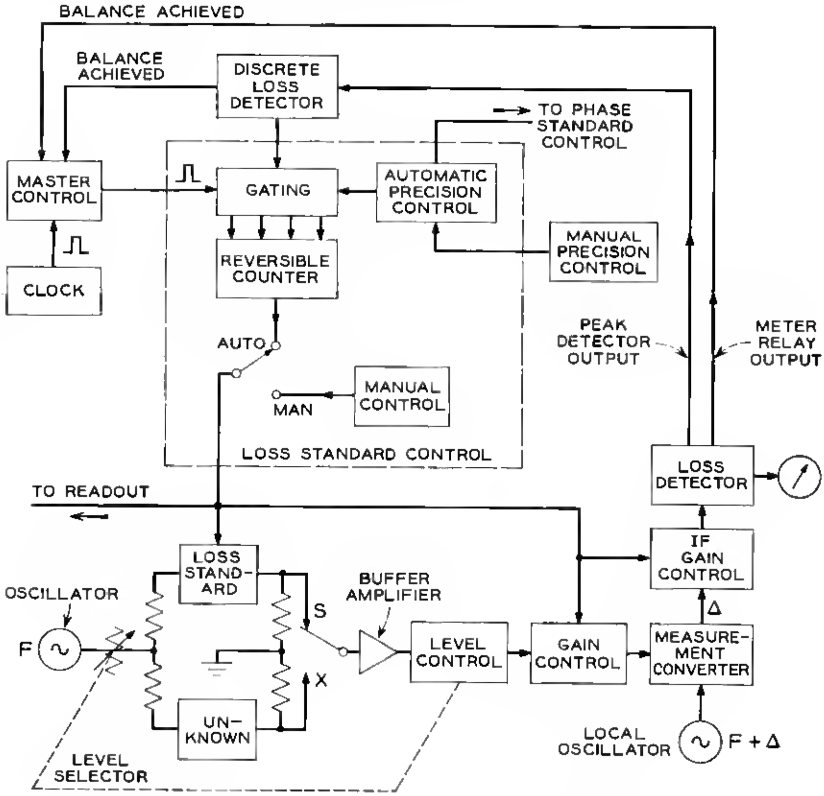

Fig. 8 — Simplified block diagram — loss measuring circuit.

sampling rate to be chosen independently of the characteristics of the unknown network.

The buffer amplifier is followed by a level control circuit, ganged to the oscillator output level selector in such a way that the S path input level into the loss detector is kept constant ± 0.1 db as the oscillator output level is varied. This is also the raison d'être for the gain control circuits which are ganged to the loss standard. The gain control circuits provide an S path input level at the loss detector that is constant to ± 0.1 db over the full loss measuring range of the set. Maintenance of this constant level makes possible a loss detector sensitivity constant to ± 1 per cent. The gain control circuits also provide a constant S path input level into the measurement path converter for losses up to 80 db. This eases the linearity and crosstalk requirements on the converter.

The measurement path converter linearly translates the amplitude of the 20- to 20,000-cps measurement signal to the 97-kc IF. A beam deflection tube is used as the converter. The tube was used because of the high degree of balance which can be maintained for the local oscillator signal in the modulator output. The voltage gain to this input is less than -76 db. This balance eases the IF filter requirements for measurements at low frequencies, since at the lowest measurement frequency of 20 cps, the local oscillator frequency is within 20 cps and the upper sideband is within 40 cps of the desired lower sideband. The narrow-band crystal filter (28-cycle noise bandwidth) is used for automatic measurements at frequencies below 500 cps. In the manual and semiautomatic modes at measurement frequencies above 500 cps and in cases where a maximum signal-to-noise ratio is not required, the wideband filter (280-cycle noise bandwidth) is used. It was the settling time of these filters that determined the maximum switching rates of the sampling relay.

The loss detector compares the amplitudes of the IF signal for the S and X positions of the sampling relay. The difference in amplitudes is proportional to the difference in loss between the loss standard and the unknown. This loss difference, or unbalance, is displayed on a calibrated panel meter with three full-scale ranges, 0.1, 1, and 10 db. A meter relay is connected in series with the panel meter and is used to give a discrete indication to the master control when the loss unbalance is less than 0.015 db.

A discrete loss detector is connected to the loss detector in parallel with the meter circuits to provide additional discrete indications of the loss unbalance. The discrete loss detector is an eight-level analog-digital converter. The eight levels correspond to loss unbalance magnitudes less than 0.01 db or greater than 0.01 db, 0.03 db, 0.1 db, 0.3 db, 1 db, 3 db,

and 10 db, together with the sign. The indications are used for balancing the loss standard and for loss programming.

The loss standard control operates the relays of the loss standard in accordance with the settings of the front panel control knobs in the manual mode, and in accordance with the state of a 4-stage reversible decimal counter in the semiautomatic and automatic modes.

When an automatic loss balance is being made, balancing pulses generated by the master clock are gated into the loss standard control by the master control. The loss standard control then gates the pulses into the counter stage controlling the most significant decade requiring a change. Control for this gating is furnished by the discrete loss detector, and the result is a rapid balancing sequence.

Since the detector signal-to-noise ratio decreases as the measured loss increases, automatic control of the precision of balance is required during automatic measurements. The precision of automatic balance versus measured loss is given in Table I. For cases where precision less than that provided by the automatic control is necessary or desirable, a manual precision control is provided.

When a balance has been achieved, as indicated by signals from the discrete loss detector and the loss detector meter relay, balancing pulses are no longer gated to the loss standard control. If the balance achieved condition is maintained for a period of 4 successive balancing pulses, the loss balance is considered complete and, in the automatic operation mode, the phase balancing step is begun.

5.3 *Phase Measuring Circuit*

The phase measuring circuit is shown in Fig. 9. Since the phase detector indication is affected by the input levels, the loss balance must precede the phase measurement.

The sampling relay in the comparison unit samples the phase difference in the S and X paths. This phase difference is translated by the measure-

TABLE I

Measured Loss	Precision of Automatic Balance
0–39 db	0.01 db
40–59 db	0.03 db
60–79 db	0.1 db
80–89 db	0.3 db
90–99 db	1 db
100–120 db	3 db

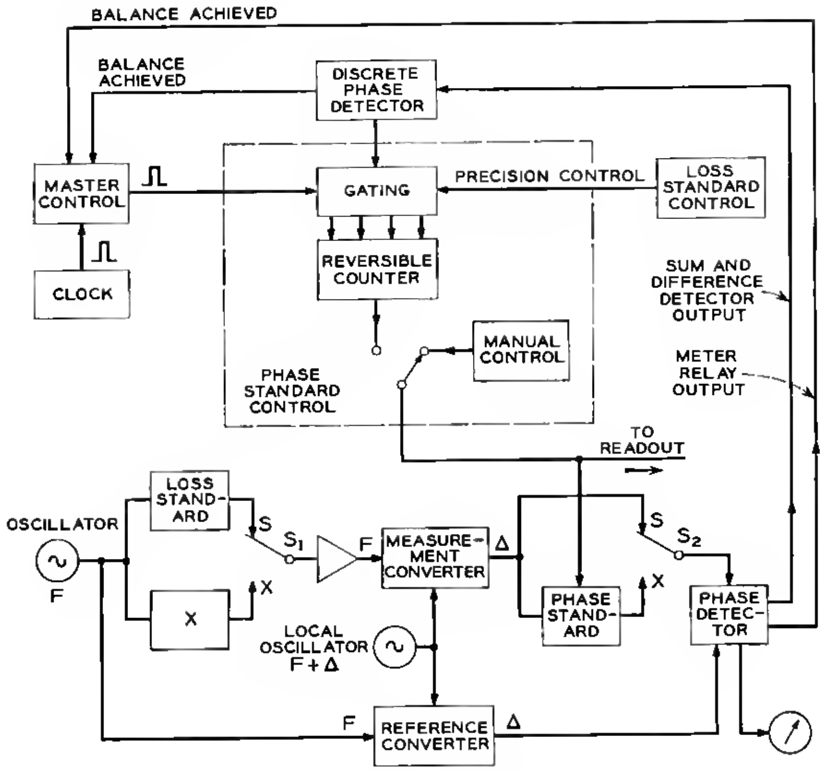

Fig. 9 — Simplified block diagram — phase measuring circuit.

ment path converter to its negative at IF. The phase standard is switched in synchronism with the sampling relay in such a way that the phase variation at the measuring path input to the phase detector is equal to the phase difference between the unknown and the phase standard. This phase is compared to the constant phase of the reference path by the phase detector, and the phase difference between the unknown and the phase standard is displayed on a calibrated panel meter. The meter has three full-scale ranges, 1°, 10°, and 80°. A meter relay is also used here to give a discrete indication when the phase unbalance is less than 0.15°. The deflection sensitivity of the phase detector is maintained constant within ±1 per cent by controlling the input levels to the phase detector and by using a voltage-controlled phase shifter in a feedback loop, so that the output of the phase detector will be zero when the sampling relays are in the S position.

The phase standard is a digital standard which can be relay-switched to vary phase from 0 to 360° in 0.1° steps. The phase standard is balanced in essentially the same way as the loss standard. The precision of the phase balance, which depends on the signal-to-noise ratio, is determined either by the insertion loss of the network being measured or by the setting of the manual precision control.

5.4 *Program Control Circuit*

As shown in Fig. 10, the program control receives inputs from the discrete loss and phase detectors, the frequency counter, and the oscillator Δf counter. When the oscillator is being swept during semiautomatic or automatic operation, the frequency counter is cycled continuously, using a 0.1-second time base. The swept frequency is measured with a maximum error of 22 cps, and the output from the frequency counter is compared to the settings of the range selector switches. This comparison indicates which of the selected ranges the measurement frequency lies in, and also determines which set of Δf, ΔL, and $\Delta\theta$ switches control the program. The settings of the appropriate Δf, ΔL, and $\Delta\theta$ switches are

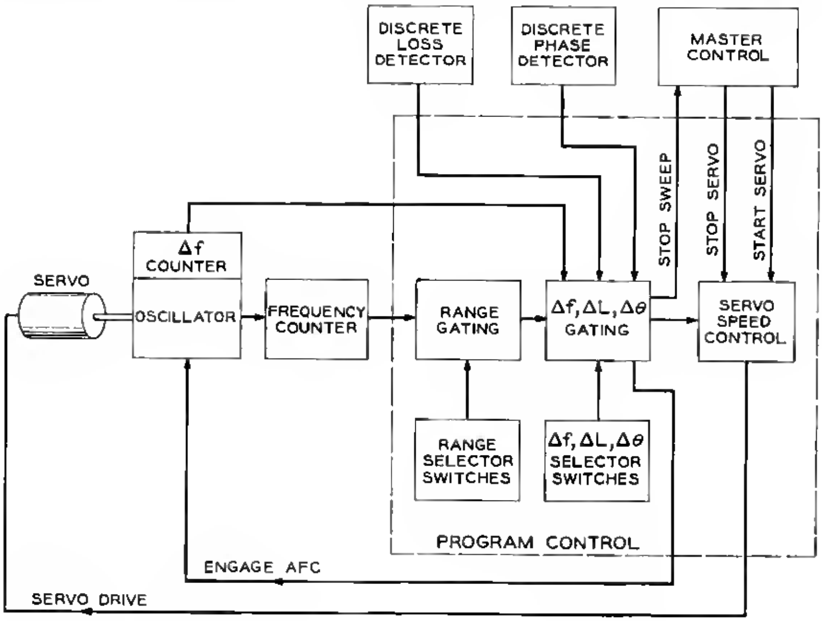

Fig. 10 — Simplified block diagram — programming circuits.

compared to the outputs of the Δf counter, the discrete loss detector, and the discrete phase detector. Coincidence circuits indicate a match when it occurs and stop the oscillator sweep. If the oscillator is stopped because of a Δf interval being equalled, a signal is sent to the oscillator to engage the AFC loop and reset the Δf counter.

The speed of the oscillator sweep is controlled by the program control. This speed is proportional to the programmed ΔL or $\Delta\theta$ interval, whichever requires the slower speed. When the indicated loss or phase unbalance reaches $\frac{1}{3}$ of the programmed interval, the servo speed is reduced. These two controls of the oscillator sweep speed make possible a reasonably short sweep time without, at the same time, causing large errors in the programmed intervals due to overshoot. Section 6.2.3 shows the considerations involved in the choice of sweep speeds.

5.5 *Other Important Circuits*

In addition to the circuits already discussed, there are several others which deserve a brief description.

5.5.1 *Frequency Counter*

The frequency counter can be controlled to measure frequency with 3 time bases. When used with the 1-second and 10-second time bases, the counter takes a single measurement, and the reading is used for the visual and punched tape readouts. When the 0.1-second time base is used, the counter takes measurements continuously, and the readings are used to provide inputs to the range control circuit.

5.5.2 *Readout Control*

The front panel of the readout control contains the in-line readout indicators to display the measured frequency, loss, and phase and 6 selector switches to provide an identification number for the punched tape readout. The readout control unit also contains the required translators for the visual and punched tape readouts and the parallel-to-serial converter for the tape readout. A circuit is also provided to interrupt the recorded readout in the event of a failure in the data parity check.

5.5.3 *Master Clock*

All timing pulses necessary for the system are generated by the master clock. The clock has two rates, 10 cps and 1.6 cps, for use with the wide- and narrow-band IF filters, respectively. Pulses from the clock go to the

sampling relays, loss detector, discrete loss detector, loss standard control, phase detector, discrete phase detector, and phase standard control.

5.5.4 *Master Control*

Sequence control is the best description of the function of the master control unit. In the automatic mode, it monitors the operation of the balance loss, balance phase, read frequency, print out, and sweep frequency steps, and controls the order in which they are operated. The master control panel contains pushbutton controls to operate each of these steps in the semiautomatic mode. An error control is provided which allows the operator using the manual or semiautomatic mode to designate the most recently punched data point as an error. Finally, the panel contains the all-important control which the sorcerer's apprentice could not find, the one marked "stop."

VI. SYSTEMS CONSIDERATIONS WHICH INFLUENCED TEST SET DESIGN

The most important objectives in the design of the test set were to achieve the specified measurement ranges and accuracies and to provide the means for rapid and accurate data selection based on settings of the program control. Some of the factors which were considered in the test set design will now be discussed.

6.1 *Measurement Errors*

The following sources of error were considered in the test set design:
(a) loss standard imperfections
(b) phase standard imperfections
(c) insertion ratio errors due to misterminations
(d) harmonics and modulation products
(e) IF bandwidth and switching rate of comparison unit
(f) random noise
(g) power frequency pickup
(h) crosstalk and
(i) drift.

6.1.1 *Loss Standard*

It was required that all steps from 0 to 40 db be accurate to ±0.002 db and that the phase shift of the loss standard be independent of loss to within ±0.02° for frequencies from 20 cps to 20 kc. To meet the requirements on attenuation accuracy, stable wire-wound resistors with the

required accuracy were used. To meet the phase requirements, it was necessary that the design impedance of the loss standard be made less tban 600 ohms. For convenience in measuring the loss and phase of the standard with existing equipment, the design impedance was made 75 obms. After compensation, variations of loss setting produced no observable phase changes on a phase detector with 0.01° sensitivity.

6.1.2 *Phase Standard*

All steps of the phase standard were required to be accurate to ±0.02°, with the output level variations between any two steps less than 1 db. The unit consists of 3 stages of relay-switched RC elements. Low reactance, wire-wound resistors and high-Q temperature-compensated silver mica capacitors are used to achieve the necessary component stability of 0.01 per cent and the low output level variation. The phase standard was calibrated on the X75706 TMS (Ref. 1, p. 1515), which has tbe required phase accuracy of 0.02° at 97 kc. The phase standard is also frequency-sensitive, so a requirement of ±0.01 per cent, or about ±10 cps, was placed in the IF frequency stability.

6.1.3 *Errors Due to Misterminations*

For the comparison circuit shown in Fig. 11, the maximum error, φ, in measuring insertion loss and phase between nonideal terminations is approximately,[2]

$$\varphi = |S_{11}G| + |S_{22}L| + |GL| + |S_{11}'G'| + |S_{22}'L'| + |G'L'|$$

where φ is in nepers and radians. The quantities G, L, S_{11}, and S_{22} are the reflection coefficients of the generator termination, load termination,

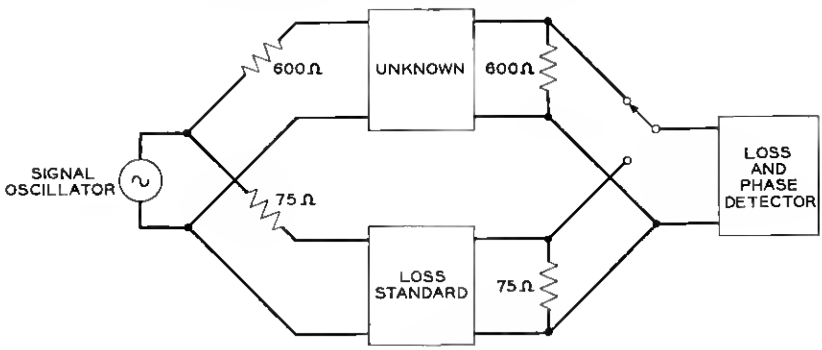

Fig. 11 — Comparison circuit.

and the physical input and output scattering coefficients of the network under test, all taken with respect to 600 ohms. The quantities G', L', S_{11}', and S_{22}' are similarly defined for the loss standard path in the comparison circuit and are taken with respect to 75 ohms.

G, L, G', L', S_{11}', and S_{22}' are under the designer's control. The resistor elements used in the generator and load terminations are within 0.05 per cent of nominal, and in general the scattering parameters S_{11}' and S_{22}' of the loss standard are much smaller than S_{11} and S_{22}. Thus, for an unknown with scattering coefficients as large as 0.2, the maximum error will be $2 \times 0.2 \times 0.00025 = 10^{-4}$. This corresponds to an error of 0.0009 db or 0.006°.

6.1.4 *Harmonics and Modulation Products*

One group of products of special concern are those which produce spurious signals of frequency F at the input to the IF converter and of frequency Δ at the output of the IF converter. These products are: harmonics of F present in the oscillator output, Δ or $F + \Delta$ present in the oscillator output, and F or Δ present in the $F + \Delta$ signal. The requirement on the maximum magnitude of these products depends on the linearity of the gain and level control amplifiers and the IF modulator linearity and gain. Requirements were placed so that all spurious sources of Δ at the IF modulator output are 65 db below the IF signal for losses of 50 db or less and 20 db below the IF signal at 120 db loss.

Other products of special concern are the $F + \Delta$ and $2F + \Delta$ products in the IF converter output as F approaches 20 cps. The IF converter is balanced against $F + \Delta$ and maintains a $\Delta/(F + \Delta)$ ratio of 30 db or greater in the converter output. No balance is obtained against $2F + \Delta$, so the narrow-band IF filter must provide 35 db discrimination at $F + \Delta$ and 65 db discrimination at $2F + \Delta$. This very steep cutoff requirement on the IF filter imposes the limitation on the operating speed of the measuring set.

6.1.5 *IF Bandwidth and Switching Rate of Comparison Unit*

The filter that provides the necessary narrow IF bandwidth will also have a large envelope delay and long settling times. The total filter transient time determines the maximum switching rate of the comparison unit and the maximum rate at which the loss and phase standards can be balanced. Since one of the objectives in automating the set was to operate at high speed, a wide filter bandwidth is desirable. As a compromise, two IF filters are used. During automatic operation from 20 cps to 500

cps, a filter with a 3-db bandwidth of 18 cps is used and from 500 cps to 20 kc, the 3-db bandwidth is 180 cps. The filters have a maximally flat delay characteristic which gives a relatively short transient time.[3] The two switching rates used are 10 cps and 1.6 cps.

6.1.6 *Random Noise*

The presenee of random noise in tbe measuring circuit will cause both fixed and fluctuating errors in the indications of the loss and phase detectors. The fixed errors cannot be detected and thus produce errors in the measurements. The fluctuating errors can be detected and eliminated, providing they are averaged for a sufficiently long period. No averaging is done in the discrete detectors used in automatic balancing of the loss and phase standards, so the precision of automatic balance is reduced as tbe noise level increases. The precision of automatic balance versus level is given in Section 5.2.

The noise bandwidth of the system is determined by the bandwidth of the IF filters. The noise bandwidth of the narrow filter is 28 cycles and that of the wide filter is 280 cycles. For losses greater than 20 db, the low-level point of the system is at the comparison switch (S_1, Fig. 6). The noise figures of the 0-db buffer amplifier and the level and gain control amplifiers which follow S_1 determine the system noise figure. The system noise figure varies with frequency, being 28 db at frequencies above 1 kc and increasing to 45 db at 20 cps.

For 40-db loss measurements and 0-dbm sending level, the minimum signal is -40 dbm. At frequencies greater than 1 kc, and for a 280-cycle noise bandwidth, the minimum signal-to-noise ratio is 81 db, which is greater than the required for a measurement witb 0.01 db precision. For 120 db loss and a 28-cycle noise handwidtb, the minimum signal-to-noise ratio is 11 db. This allows 3-db precision with the discrete detector.

6.1.7 *Power Frequency Pickup*

Harmonics of the power frequency which are coupled into the measurement circuits also cause fixed and fluctuating errors in the loss and phase detector indications. These errors occur whenever the measurement frequency is close enough to one of these harmonic frequencies that the IF filter does not discriminate against it. In the automatic and semiautomatic modes, a blanking circuit is provided to prevent the ΔL and $\Delta\theta$ program controls from stopping the oscillator within ± 15 cps of 60, 180, or 300 cps. Inside these bands, the outputs from the discrete detectors are not reliable for programming and balancing. With the use of the

blanking, measurements may be made over the 20- to 20,000-cps range with a precision of 0.01 db for losses up to 40 db.

6.1.8 *Crosstalk*

Since the signal level into both modulators is kept constant for losses up to 80 db, crosstalk at IF or through the modulators was not a difficult problem.

The main source of crosstalk was in power supply coupling. Decoupling is especially difficult in those units operating at 20 cps, since effective reactive components become very large at that frequency. Some decoupling was effected by using separate power supplies, and in other cases an active filter was used to provide decoupling and attenuation of power supply ripple.

6.1.9 *Drift*

The 1.6-cps switching rate requires that drifts in the common path circuits be less than 0.01 db and 0.1° during the 0.6-second period.

6.2 *Programming Errors*

As discussed in Section II, the measurement programming permits the division of the measurement frequency range into as many as 5 bands, and in each of these bands a selection of Δf, ΔL, and $\Delta\theta$ intervals may be made. A natural question to ask is, how accurate are these intervals when point-by-point measurements are made?

6.2.1 *Range Control Error*

As the input to the frequency counter is varied at a rate of K cps/second over the counting period τ seconds, the maximum error, E, in the counter reading will be,

$$E = \frac{K\tau}{2} + \frac{1}{\tau}.$$

For $\tau = 0.1$ second and with the maximum sweep rate of 240 cps/second, an error of 22 cps can result. This error in counter reading can cause, in the worst case, a range control error of 33 cps.

6.2.2 Δf *Program Accuracy*

The low-inertia servo motor selected for the oscillator sweep drive and the relatively high-speed Δf recognition circuitry make it possible to stop

at any Δf frequency interval with an overshoot of less than 10 cps. When the oscillator drive is stopped, the oscillator frequency is phase locked to a multiple of a 100-cps frequency standard, thus giving exact Δf intervals.

6.2.3 *ΔL and $\Delta\theta$ Program Interval Accuracy*

Measurements of the ΔL and $\Delta\theta$ program intervals are made with a frequency source which is being swept, on unknowns with finite bandwidths, using a narrow-band detector. In most cases, the delay introduced by the detector will be long compared to the delay present in the measured networks. The inertia of the oscillator drive motor and the detector delay will cause the oscillator to overshoot the frequency where the ΔL or $\Delta\theta$ interval is exactly reached. Referring to Fig. 12, it is seen that the program error E_L, for loss is

$$E_L = n \log_2 \frac{f_2}{f_1}$$

where n = loss slope in db/octave
f_2 = frequency where oscillation is stopped
f_1 = frequency where ΔL is reached.
For a delay of τ in recognizing ΔL and a sweep speed of K cps/second

$$E_L = n \log_2 \left(1 + \frac{K\tau}{f_1}\right) \doteq 1.44 \frac{nK\tau}{f}$$

for small E_L and f_1 arbitrary. If the fractional program error P is defined as

$$P = \frac{E_L}{\Delta L}$$

then the acceptable rate of sweep for loss intervals is

$$K = \frac{1}{1.44\tau} P \frac{f\Delta L}{n}.$$

The desirable fractional program error and τ are considered constants, and ΔL depends on the program input. It can be shown that by using the differentiated output of the loss detector fed back to control the oscillator sweep speed, K, a constant fractional program error can be achieved. Similar results can be obtained for phase programming.

The approach used in this set was to sweep the oscillator at a rate proportional to ΔL over the loss range from 0 to $\Delta L/3$ in such a way that a program error of just less than 60 per cent will occur. When $\Delta L/3$ is recognized, the sweep rate is reduced to about $\frac{1}{6}$ of the original rate to

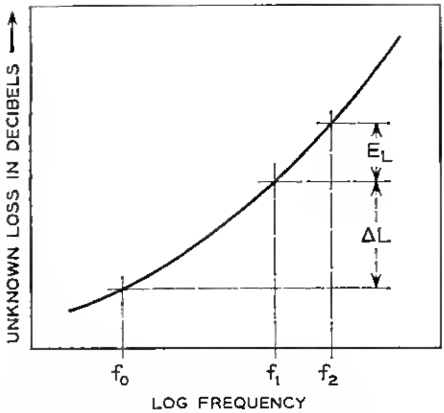

Fig. 12 — ΔL program error.

limit the overshoot to something less than 10 per cent. The sweep for phase intervals is controlled in the same way, and in cases where both ΔL and $\Delta\theta$ are programmed, the slower sweep speed called for is used. The discrete detectors which measure the ΔL and $\Delta\theta$ intervals are accurate to ± 2 per cent.

6.3 *Operating Speed*

The maximum speed of operation of the set is obtained in the automatic mode. When the set takes a data point, it goes through a cycle consisting of sweep frequency, balance loss, balance phase, read frequency, and print out.

As discussed in Section 6.2, the sweep rate is limited by the allowable program error. The sweep period could be minimized if a more complex feedback arrangement were used along with an oscillator drive motor with a 1000:1 speed range. The motor which was used has a speed range of 15:1 and the maximum sweep speed is 240 cps/second.

In the balance loss operation, the IF filter forms part of the control loop. The long envelope delay and settling times associated with the narrow-band filter constitute almost all of the loop delay, with the remainder being the conversion time of the discrete detector and the delay of the balancing pulse gates. The balancing rate is 10 pps with the wide-band filter and 1.6 pps with the narrow-band filter. Even though the IF filter is not in the balance phase control loop, for practical reasons the balancing rate and logic are similar to those used in the loss standard. A timeout of 4 pulses is used after each of the balances before the balance is considered achieved.

In the read frequency operation, either a 1-second or 10-second time base is used for the frequency counter.

The speed of the readout is limited by the maximum speed of the recording tape punch and the stepping switch used in the parallel-to-serial data conversion. Without contact protection, the stepping switch is about 3:1 faster than the tape punch. Since 40 characters are punched at each measurement point and the maximum speed of the punch is 20 characters per second, the lower bound for readout is 2 seconds. The actual readout time, with contact protection on the stepping switch, is just under 3 seconds. Section 7.4 gives the breakdown of time in each step of a typical cycle.

VII. RESULTS WITH THE AUTOMATED SET

Tests were made to determine the measurement range and accuracy of the set. Selected networks were used to determine the accuracy of programmed intervals and the operating speeds, and to evaluate to some extent the efficiency of data selection.

7.1 *Measurement Accuracy*

Verification of the loss and phase accuracies of the set was carried out by a process of measuring a number of calibrated loss pads and delay networks individually and in combination. These measurements showed that the objectives of 0.01 db and 0.1 degree accuracy were met for losses up to 40 db. A nominal 120-db loss was measured as 114 db.

7.2 *Program Accuracy*

Measurements were made using selected networks to determine the accuracy of the Δf, ΔL, and $\Delta\theta$ intervals.

7.2.1 Δf *Program Accuracy*

When a programmed Δf limit is reached, the oscillator is then phase locked to a 100-cps frequency standard so that the frequency intervals are, for all practical purposes, exact. Some jitter and 100-cps sidebands do appear at the oscillator output, but the resulting variations in the instantaneous oscillator frequency are less than 0.003 per cent or 0.03 cps, whichever is larger.

7.2.2 ΔL *Program Accuracy*

Each of the ΔL intervals was programmed on a network with the maximum loss slope which can be measured to 0.01 db (0.12 db/cps).

The error in the programmed intervals is 10 per cent or 0.05 db, whichever is larger.

7.2.3 $\Delta\theta$ *Program Accuracy*

Each of the $\Delta\theta$ intervals was programmed on the maximum phase slope which can be measured to 0.1° (1.44°/cps). The error in the intervals is 15 per cent or 0.8°, whichever is larger. From these results, it can be seen that the minimum frequency change that will occur in the presence of steep loss or phase slopes is about 0.5 cps.

For $\Delta\theta$ intervals programmed on a 25-μsec delay line (slope 0.01°/cps), the program error is 2 per cent or 0.1°, whichever is larger.

7.3 *Data Selection*

7.3.1 *Delay Equalizer*

A simple example of automatic data selection is provided by measurements on a delay equalizer. Loss and pbase are measured from 500 to 3400 cps, and loss must be known to the nearest 0.1 db. The program used is $\Delta L = 0.1$ db and $\Delta f = 100$ cps. Delay is calculated on a computer from the phase measurements, and the ΔL program characterizes the unknown within the required 0.1 db. The Δf program eliminates any significant uncertainty in the measurement frequencies and thus removes one source of error in the delay measurement. The data obtained are plotted in Fig. 13.

7.3.2 *Bandpass Filter*

As a second example of automatic data selection, a program was set up to a test a telegraph tone channel filter with the requirements listed in Table II.

Assuming that the band of interest is from 1 to 5 kc and that the phase linearity in the pass band is also of interest, the program was set up as shown in Table III.

The data taken are plotted on Fig. 14. In ranges 1 and 5, all of the points are taken by the $\Delta f = 300$ program, but one has the assurance that the loss did not deviate by more than 10 db between any two adjacent points. The $\Delta L = 3$ db program is used in ranges 2 and 4 where the 16-db and 7.5-db loss requirements are placed. In range 3 tbe phase change of about 220° is approximately linear with respect to frequency, so the $\Delta\theta = 30°$ program provides 7 points spaced at approximately uni-

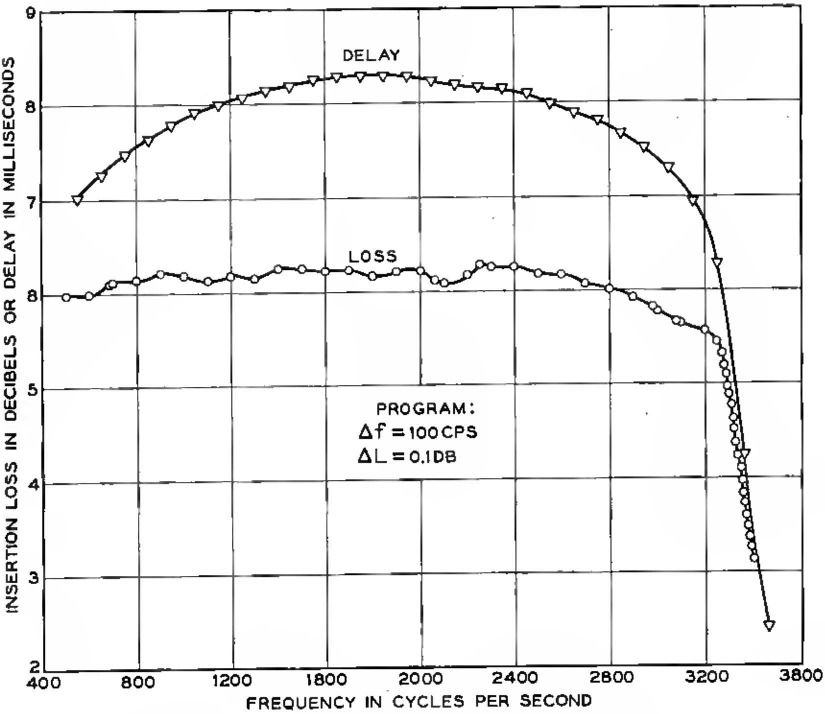

Fig. 13 — Automatic data selection — delay equalizer.

TABLE II

Loss (Relative to 2975-cps Center Frequency)	Frequency
>3 db	2975 ± 42.5 cps
>7.5 db	2890 cps
>16 db	2975 ± 170 cps
>40 db	below 2400 cps
>40 db	above 3700 cps

TABLE III

Range	Lower Frequency (kc)	Upper Frequency (kc)	Program		
			Δf	ΔL	$\Delta\theta$
1	1	2.65	300	10	off
2	2.65	2.89	off	3	off
3	2.89	3.06	off	off	30
4	3.06	3.3	off	3	off
5	3.3	5	300	10	off

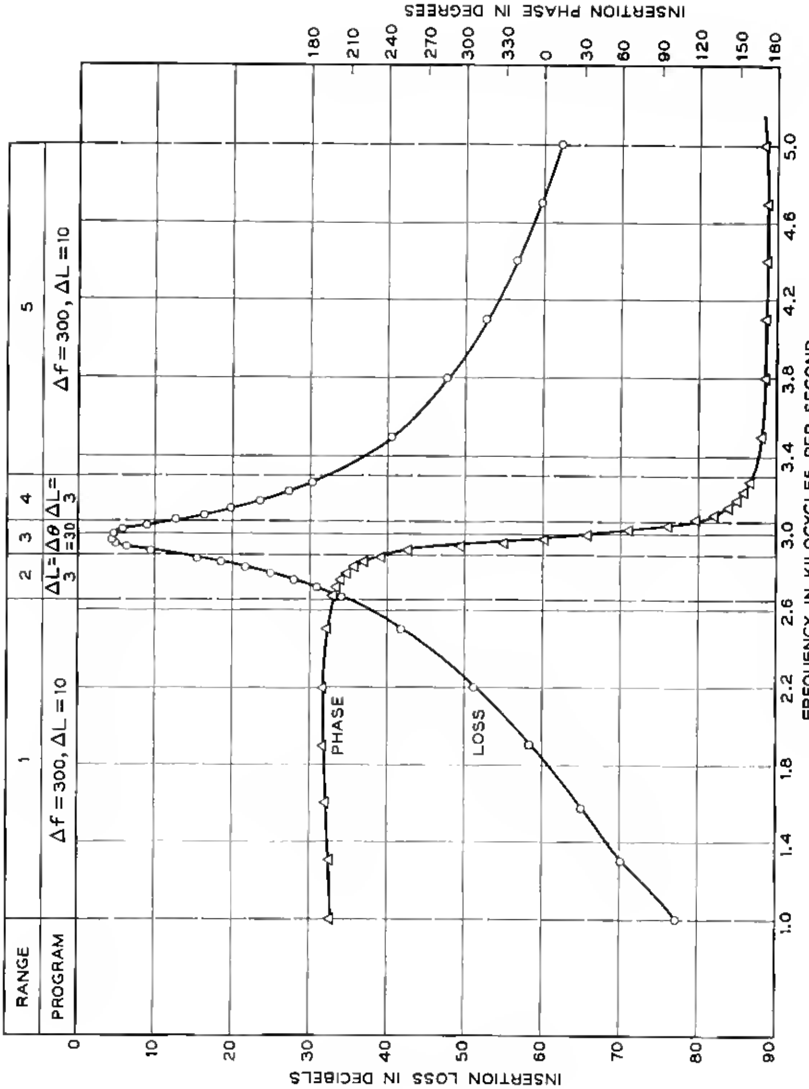

Fig. 14 — Automatic data selection — bandpass filter.

form frequency intervals. The resulting data is similar to what one would expect if it were taken by a capable human operator.

7.4 *Operating Speed*

The program described in Section 7.3.2 required 6.5 minutes to run, with an average of 14 seconds required for each point. This average time per point can be broken down as shown in Table IV.

In general, except for the read-out step and the miscellaneous delays, the time required for each step varies according to the switching rate used, the size of the programmed intervals, the precision of the measurements, and the unknown being measured. However, from the data taken so far, 14 seconds appears to be a good average.

Manual measurements were made on the filter described in Section 7.3.2 at approximately the same points plotted on Fig. 14, and the time required for the manual measurements was more than 5 times that required for the automatic measurements. Experience indicates that the average speed of the automated set is at least 10 times that of manual sets.

7.5 *Conclusions*

An automated laboratory measuring set has been developed which makes loss and phase measurements based on a preselected program and on information fed back from the measured network. The program provides the means for accurate and relevant data selection from simple instructions based on network requirements. Automatic read-out eliminates operator read-out errors, and machine processing of the paper tape output provides flexibility in the form of output data. The possibility of us-

TABLE IV

Step	Approximate Time Required (sec)
Sweep frequency	3
Balance loss	2
Loss time out	0.5
Balance phase	2
Phase time out	0.5
Read frequency	2
Read-out	3
Miscellaneous delays	1
Total	14

ing the set in the semiautomatic and manual modes provides additional flexibility.

The higher speed of the automated set makes it possible to obtain more comprehensive data on networks being measured, with the attendant benefit to both designers and users, and this data is obtained in less time at lower cost.

VIII. ACKNOWLEDGMENTS

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